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TECHNICAL REPORT ARCCB-TR-99018

LOADING FREQUENCY AND ITS EFFECTS ON THE FATIGUE LIFE OF A723 STEEL

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OCTOBER 1999

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1999	Final

4. TITLE AND SUBTITLE

LOADING FREQUENCY AND ITS EFFECTS ON THE FATIGUE LIFE OF A723 STEEL

5. FUNDING NUMBERS

AMCMS No. 4221.23.0000.0

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER

ARCCB-TR-99018

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The fatigue life of pressure vessels manufactured from two strength levels (166 Ksi and 190 Ksi) of A723 steel has been modeled, and the life predictions using the model have verified that a field loading cycle is equivalent to a laboratory pressurization loading cycle. One key assumption in the model is that a minimum crack initiator must be present in order to attain a one-to-one correlation. If the minimum crack initiator is not present, there will be a large error between laboratory and field loading when predicting final fatigue failure. This study shows that a crack initiator greater that about 0.019 inch (for 166 Ksi yield strength steel) and 0.008 inch (for 190 Ksi yield strength steel) will result in the one-to-one correlation that is sought. No attempt has been made to model environmental effects that can greatly affect the results presented here.

14. SUBJECT TERMS

Frequency, Fatigue Life, Life Prediction, Crack Initiation

15. NUMBER OF PAGES

7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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INTRODUCTION

Classic work in the field of fatigue states that there is a frequency effect on the cycles-to-failure that can be expected when metals are tested in laboratory air. This effect can be exacerbated by factors such as waveform of the load application and environmental effects, including moisture, hydrogen, etc. (ref 1). In general terms, if the frequency of loading is slower, then lesser lives can be expected. This is due to the fact that there is more exposure time to the environment (ref 2). Figure 1 isolates the frequency effects and identifies the results that can be expected in air and in a vacuum. Note that above a certain threshold (identified by the dotted line) there is no further increase in life as a result of increased frequency.

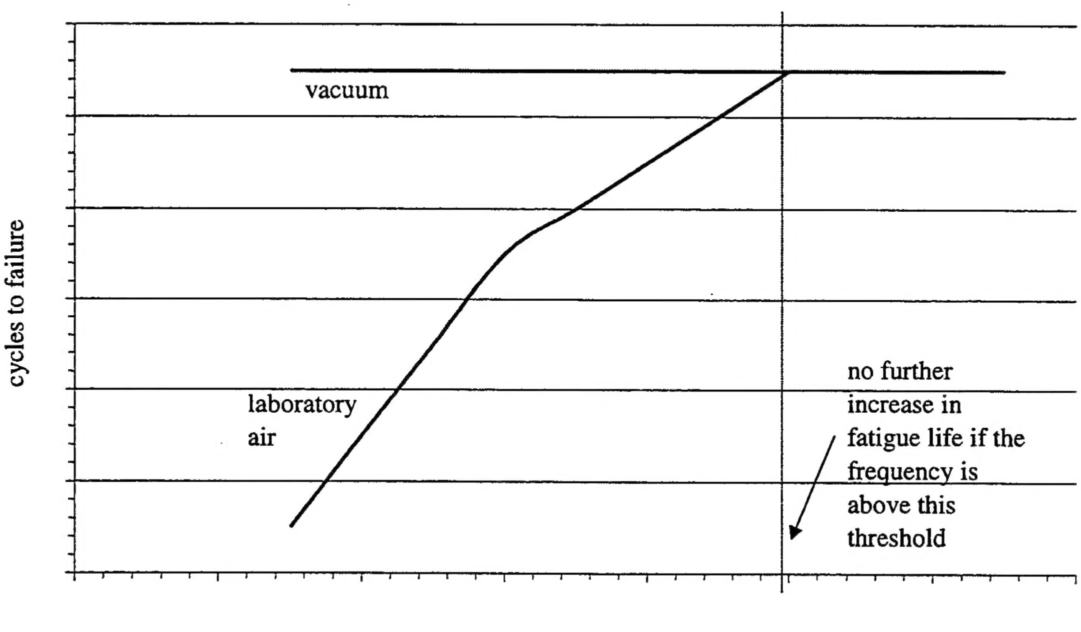

Figure 1. Effects of frequency on fatigue.

This study attempts to identify whether the cyclic frequency of loading between field loading and laboratory loading has any effect on the overall life of a gun tube. We have identified that the typical loading scenario of a field-loaded weapon is on the order of 200 Hz, while the typical fatigue loading in the laboratory for gun tubes is on the order of 0.3 Hz. Because of limitations with modern servohydraulic test machines, a loading rate of 200 Hz is impossible. Therefore, the loading rates that we could successfully test to were 0.3 Hz and 30 Hz. Remember, as stated in the previous paragraph, above a certain threshold there is no further increase in fatigue life as a result of increasing frequency. Therefore, if we successfully prove that there is no difference between 0.3 Hz and 30 Hz, then it is safe to assume that there is no difference between 0.3 Hz and 200 Hz.

TEST RESULTS

Testing was conducted with an Instron 10-kip servohydraulic test machine. A fully automated control program written by Fracture Technology Associates of Pennsylvania was utilized. The program was written to conform to ASTM Specification E647 for *da/dN* testing of metallic materials. A compact specimen (CT) geometry with the following dimensions was utilized for all tests: W = 1.575 inches; t = 0.395 inch; H = 0.945 inch; and notch depth = 0.350 inch. Premium A723 Grade 2 was the gun steel chosen. Because of an ever-increasing interest in higher strength A723 steel for future applications, two heat treatments were investigated, including the standard yield strength of 166 Ksi and a yield strength of 190 Ksi. All testing was conducted in load control, in laboratory air, at a temperature of 72°F ±5°F, and at an R-ratio of 0.1.

The test results are shown in Table 1. These test results are not conclusive, in that they cannot be utilized in this form to approximate remaining life of a component. Further analysis presented in the next section will answer these questions.

Table 1. Results of *da/dN* Test Data for A723 Steel at Two Different Strength Levels

Specimen ID	0.2% Yield Strength (Ksi)	Frequency (Hz)	R-ratio	C	N
1	166	30	0.1	1.53E-10	2.94
2				3.29E-09	2.29
3				2.21E-10	2.87
4				1.41E-10	2.96
5				7.02E-10	2.63
11				1.77E-09	2.54
12				3.68E-10	2.87
Average				9.49E-10	2.73
6	166	0.3	0.1	1.97E-09	2.43
7				7.17E-09	2.11
8				6.23E-08	1.63
9				2.53E-09	2.25
10				4.90E-09	2.09
Average				1.58E-08	2.08
6	190	30	0.1	3.37E-09	2.26
7				1.43E-09	2.53
8				4.53E-10	2.86
9				1.42E-09	2.47
10				3.46E-09	2.37
11				4.16E-09	2.16
Average				2.38E-09	2.44
1	190	0.3	0.1	3.25E-09	2.29
2				1.61E-08	1.89
3				8.75E-09	2.02
4				8.16E-09	2.05
5				2.20E-08	1.79
Average				1.17E-08	2.01

ANALYSIS OF RESULTS

The test results generated from ASTM Specification E647 can now be utilized with the well-known Paris Law

$$da/dN = C\Delta K^{n} \tag{1}$$

to approximate remaining life. This equation can be integrated with the approximate closed-form ΔK solution for a gun tube

$$\Delta K = \Delta\sigma\sqrt{\pi a} \tag{2}$$

to yield

$$N_f = \frac{1}{(\frac{-n}{2}+1)(C\pi^{n/2}\Delta\sigma^{n})}[a_f^{-n/2+1} - a_i^{-n/2+1}] \tag{3}$$

where a_i is the initial detectable flaw depth, a_f is the final or critical crack depth, $\Delta\sigma$ is the applied stress (approximated here as the yield strength), and N_f is the number of remaining cycles-to-failure.

K_{Ic} for the two heat treatments was known from prior experience to be 120 Ksi√in. for the 166 Ksi yield strength, and 90 Ksi√in. for the 190 Ksi yield strength. These values coupled with the ΔK solution, yield an a_f of 0.166 inch for the 166 Ksi yield strength and 0.071 inch for the 190 Ksi yield strength.

Utilizing these inputs, we can formulate an expression for remaining life of the gun tube versus the initial detectable flaw size, a_I. The results of this formulation can be observed in Figure 2 (166 Ksi yield strength) and Figure 3 (190 Ksi yield strength). Note how sensitive the calculations for remaining life are in response to the small initial flaw sizes. As a_i becomes increasingly smaller, the approximation between remaining life for the faster and slower loading rates becomes more prominent. For the 166 Ksi yield strength material, we can clearly see that an $a_i > 0.019$ inch results in remaining lives within 100 cycles for both loading rates, and for the 190 Ksi yield strength material, if $a_i > 0.008$ inch, the remaining life is also within 100 cycles for all initial flaw sizes. It is quite possible that these estimates of a_i are overly conservative because the ΔK expression utilized is not exact for a gun tube. Had an exact ΔK expression for gun tubes been available (for short and long cracks), it would have been utilized. The ΔK expression utilized does closely approximate a gun tube for moderate and long cracks, however it has limitations for small cracks, and severe limitations for extremely small cracks.

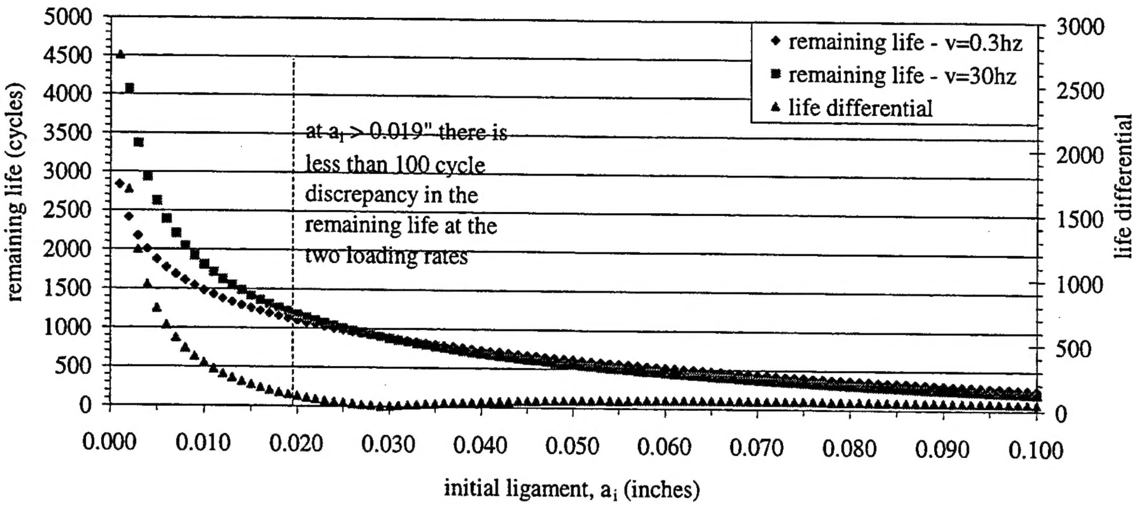

Figure 2. Frequency effects of A723 steel at yield strength 166 Ksi.

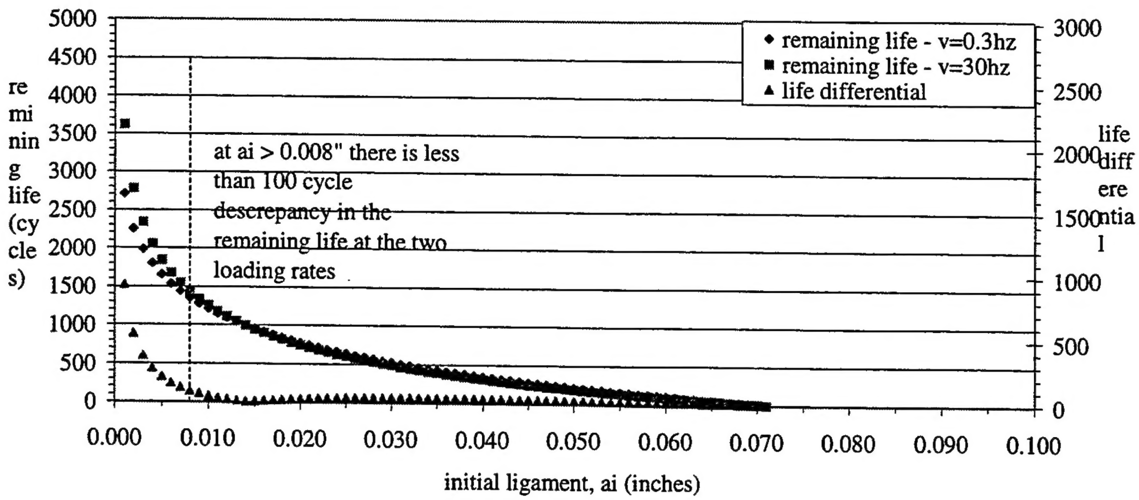

Figure 3. Frequency effects of A723 steel at yield strength 190 Ksi.

Since gun tubes are fired out in the field to induce the initial cracking, it is imperative that the initial depth of cracking be known prior to fatigue loading in the laboratory. For example, if the initial flaw depth from firing in the field were 0.002 inch and the tube was fired in the field until failure (200 Hz), the approximate life would be 4070 cycles; whereas if that same tube had been returned to the lab for fatigue cycling (0.3 Hz), the expected life would have been 2410 cycles. However, if the initial flaw depth from field firing were 0.020 inch, the expected life would be 1180 cycles in the field (200 Hz) and 1100 cycles in the lab (0.3 Hz).

CONCLUSIONS

1. This study assumes only mechanical frequency effects, and does not address environmental factors, which can greatly impact the life of a gun tube.

2. Initial flaw depth from field firing must be known in order to approximate remaining life. This requirement becomes more important as the initial crack depth goes to 0.000 inch.

3. As the initial flaw depth increases, the approximation of remaining life as a result of frequency effects becomes less prominent. For gun steel with a yield strength of 166 Ksi and an initial flaw depth greater that 0.019 inch, there is a one-to-one correlation between field loading (200 Hz) and laboratory loading (0.3 Hz). For 190 Ksi yield strength gun steel, there is a one-to-one correlation for any flaw depth greater than 0.008 inch.

4. For all practical purposes, the approximation of estimating initial flaw depths with ultrasonics is on the order of 0.015 to 0.020 inch. Hence, the flaw depths recommended above are not easily detectable in the field.

5. We know that the initial field firing of a cannon is necessary to induce cracking, and this analysis has shown that the initial flaw size for our current strength gun steels is on the order of 0.019 inch for a one-to-one correlation between field and laboratory loading. This value is likely conservative since the ΔK expression utilized in equation (2) is approximate for a gun tube, and is not ideally suited for extremely short cracks. As the initial crack depth goes toward zero, the error imposed by this approximation becomes more prominent. Since the results showed little frequency effects for longer cracks, where these expressions, and the data are known to be accurate and correct, we believe that the conservatism's built into the analysis may not be justified. Therefore, we feel that any detectable cracking of a gun tube is sufficient for a one-to-one correlation between laboratory and field loading.

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2. Dowling, N.E., *Mechanical Behavior of Materials*, Prentice Hall, 1993.

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